Soft Contribution to the Hard Ridge

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CATHIE/TECHQM, December 14-18, 2009

arXiv:0910.3590 [nucl-th]
GM, **Sean Gavin**

Phys.Rev.C79,051902,
arXiv:0806.4718 [nucl-th]
Sean Gavin, **Larry McLerran**, G. M.

The Ridge
- Hard Ridge: jet trigger
- Soft Ridge: no trigger
- Flow and jets

Long Range Correlations
- PHOBOS Data
- Flux Tubes, Glasma, and Correlations

Comparison to Experiment
- Blast Wave Flow + Glasma
- p_t Dependence
- Soft and Hard Ridge from STAR

Hard Ridge: Jet + Associated Particles

Measure

- High pt trigger
- Yield of associated particles per trigger

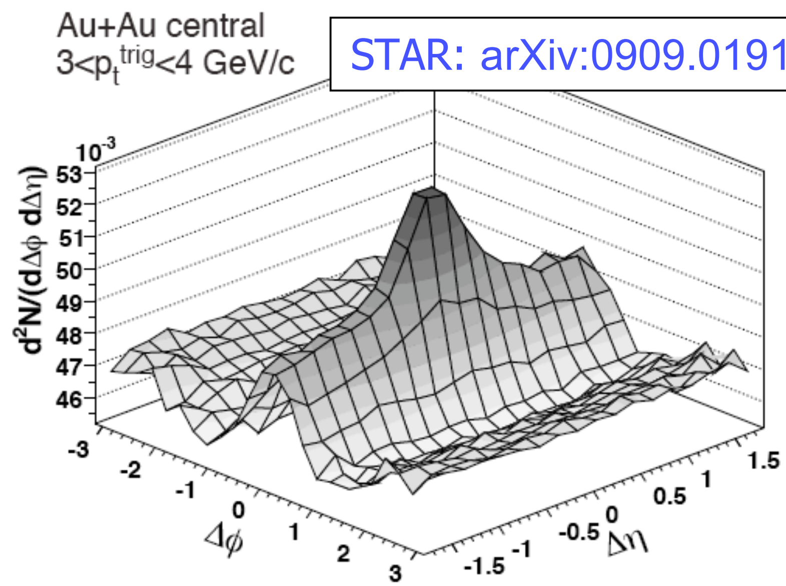
$$\frac{1}{N_{trig}} \frac{d^2N}{d\Delta\phi \, d\Delta\eta}$$

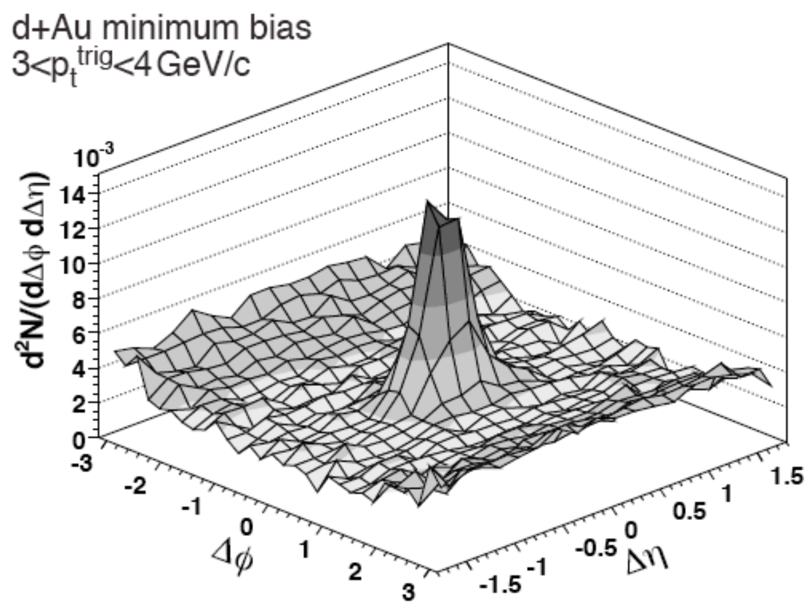
Hard Ridge: Near Side Peak

- Peaked near $\Delta\phi = 0$
- Broad in $\Delta\eta$

How does the formation of the ridge at large $\Delta\eta$ depend on jets?

STAR: arXiv:0909.0191





Soft Ridge: Untriggered Correlations

two particle correlations with no jet tag

STAR: arXiv:0806.2121

Measure

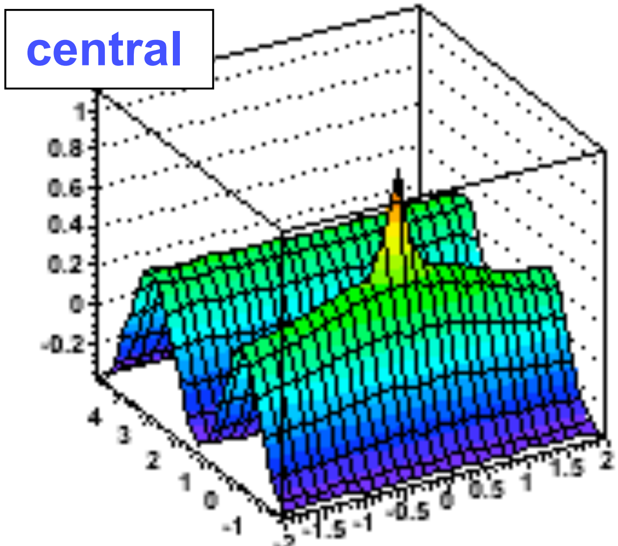
$$\frac{\Delta\rho(\eta,\phi)}{\sqrt{\rho_{ref}}} = \frac{\text{pairs} - (\text{singles})^2}{\text{singles}}$$

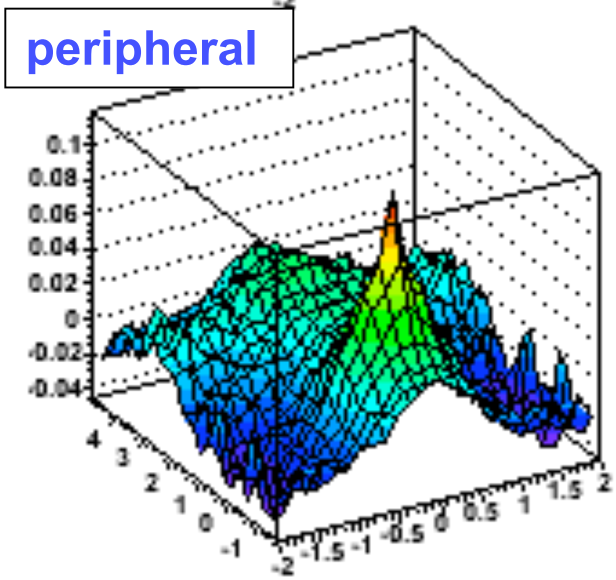
Soft and Hard Ridges Similar

- Peaked near $\Delta\phi = 0$
- Wider in $\Delta\phi$ than hard ridge
- Broad in $\Delta\eta$
- Jet peak?

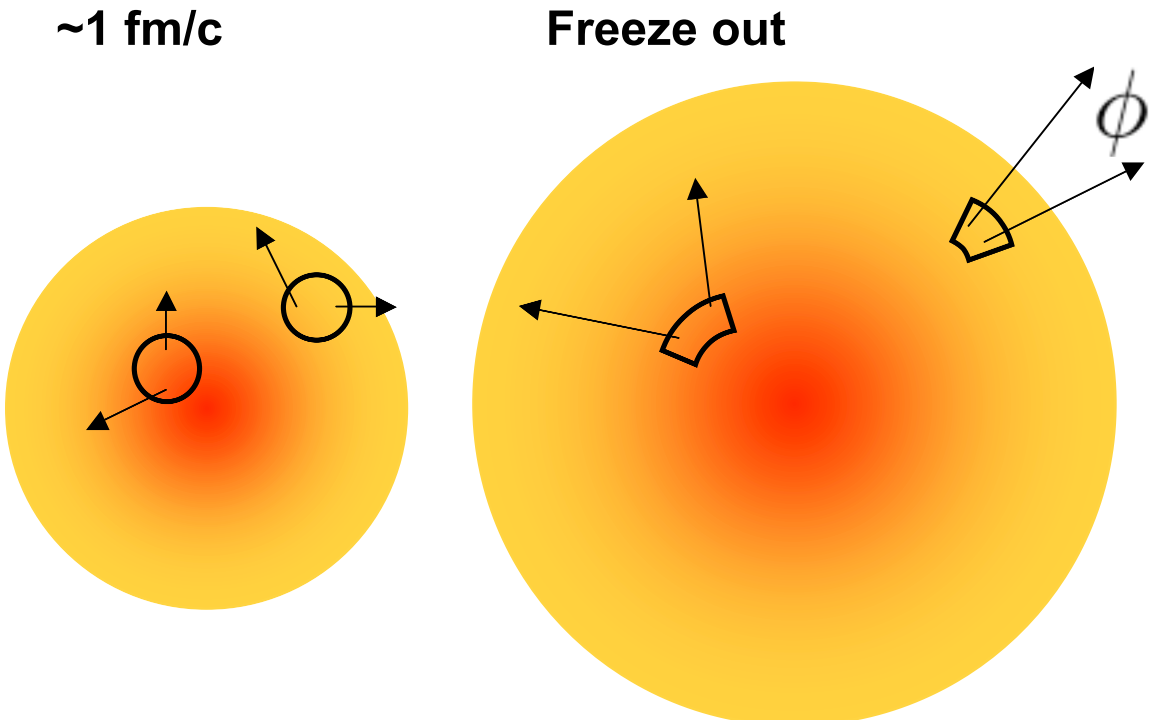
Common Features

- $\Delta\eta$ width increases with centrality
- peripheral ~ proton+proton





Near Side ϕ Peak: Flow



Azimuthal correlations come from flow.

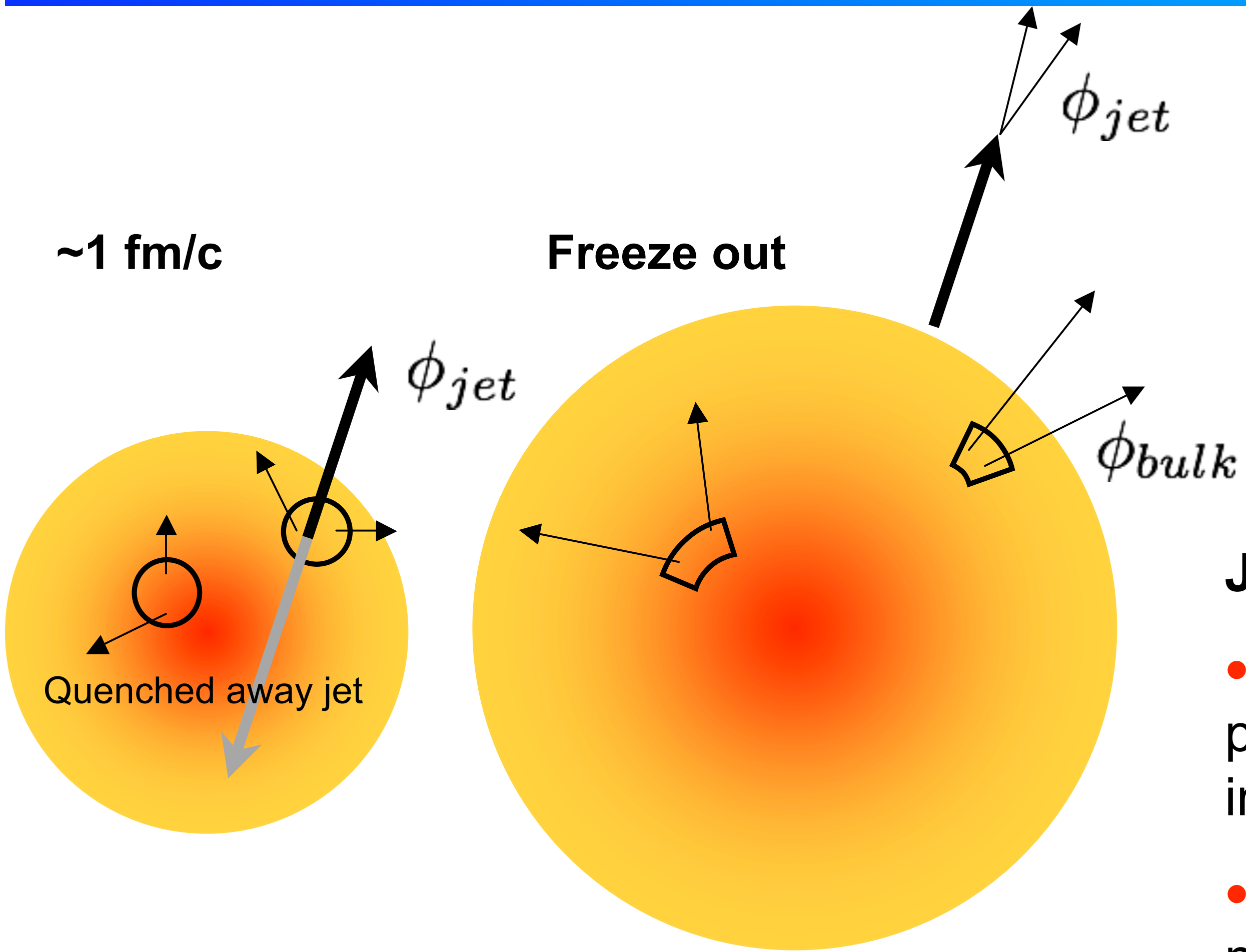
- Particles are pushed to higher p_t and and focused to a smaller azimuthal angle depending on the push.

- The ridge should narrow in ϕ with increasing p_t cuts.

- Mean flow depends on position $\vec{v}_t \sim \lambda \vec{r}_t$

- Opening angle for each fluid element depends on radial position $\phi \sim v_{th}/v_t \propto (\lambda r_t)^{-1}$

Near Side ϕ Peak: Jets + Flow



E. Shuryak, Phys. Rev. C 76, 047901 (2007)

Claim:

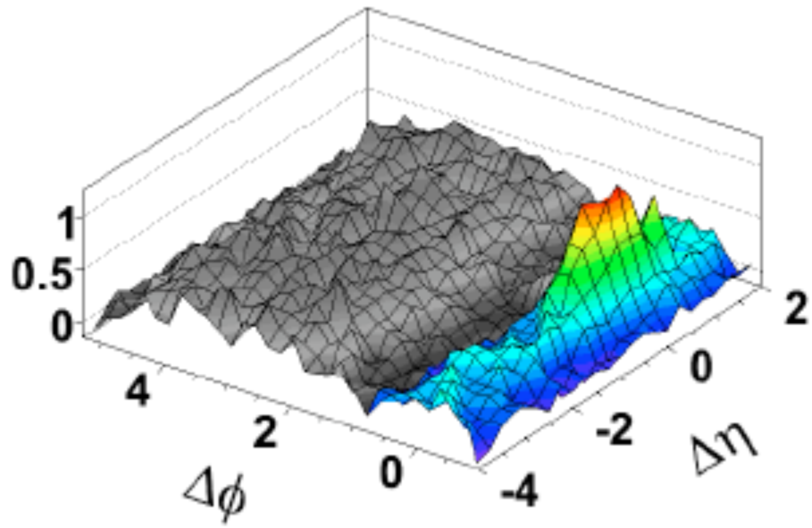
Soft ridge explained by bulk flow

Hard ridge: additional jet-bulk contribution

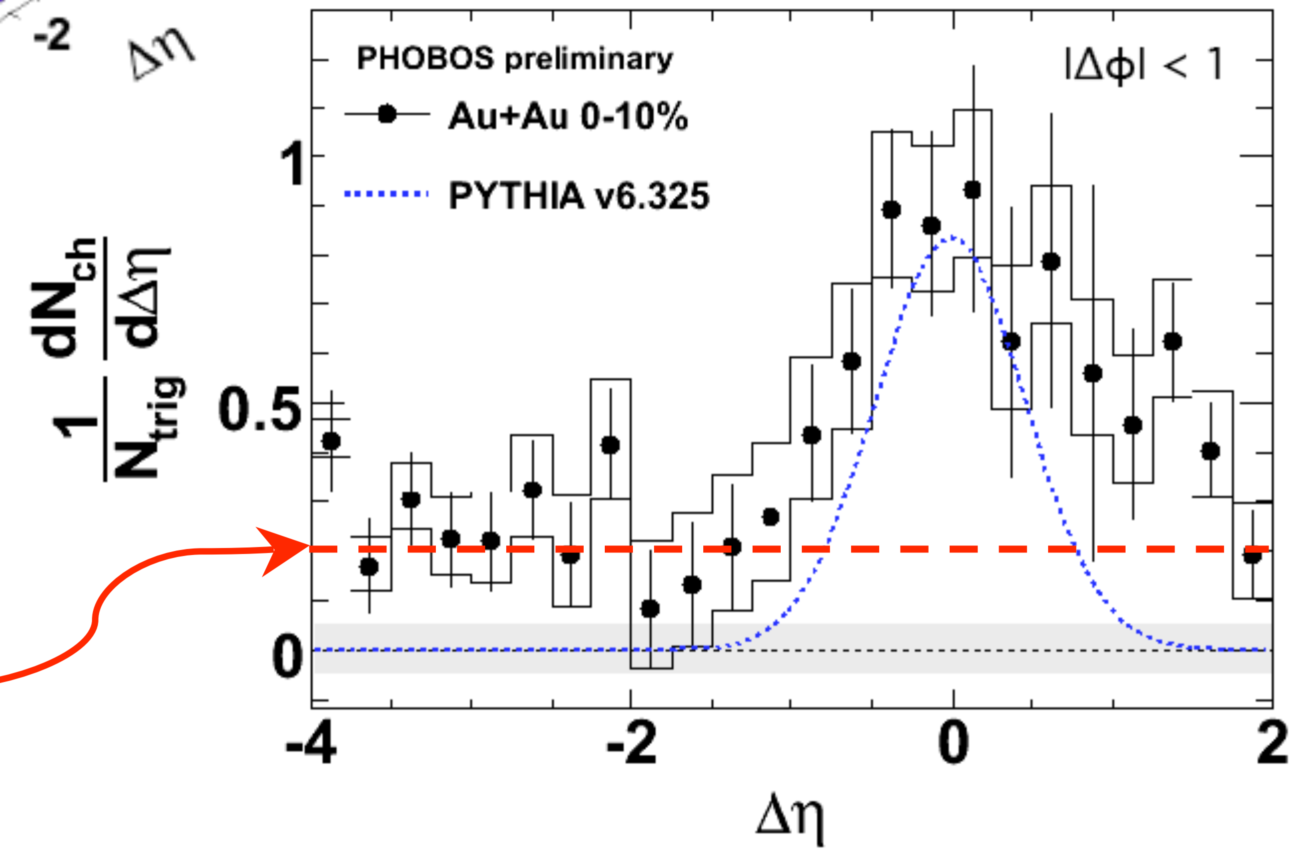
Jet Correlations With Bulk

- Correlation of flow and jet particles if produced nearby in transverse plane
- Surviving jets tend to be more radial, due to quenching.
- Bulk particles are pushed into the radial direction by flow

PHOBOS: Long Range Correlations



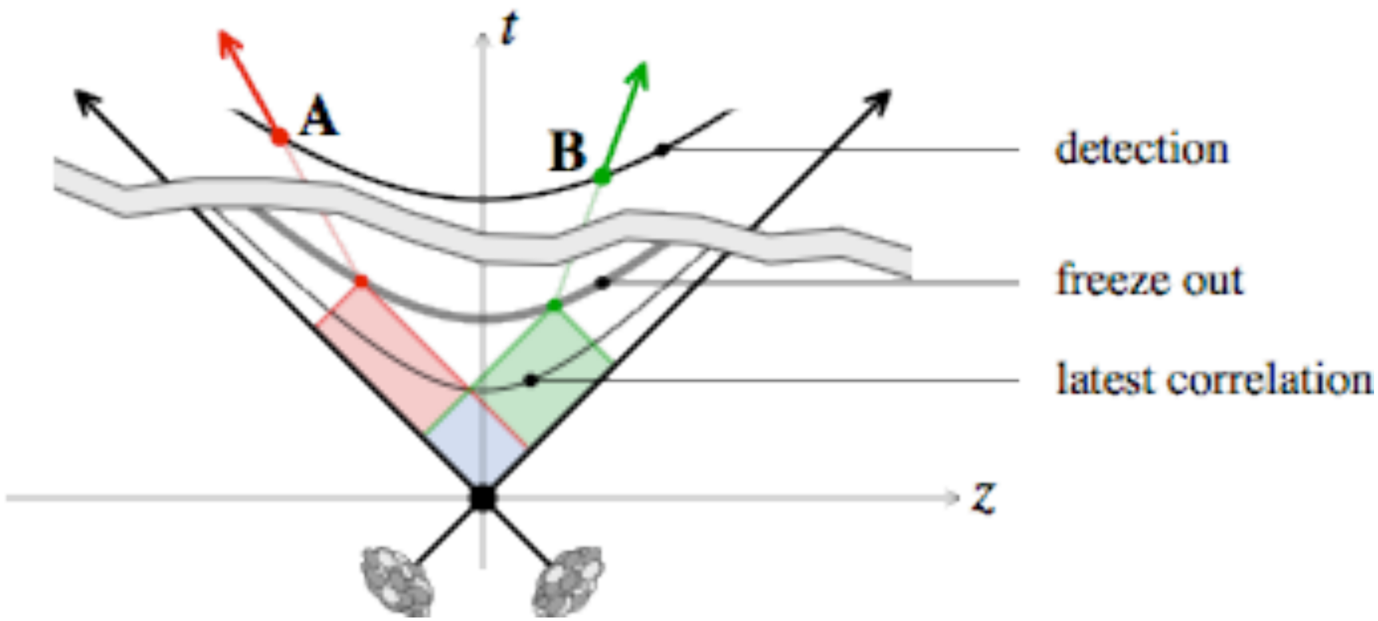
$p_T^{trig} > 2.5$ GeV/c
$p_T^{assoc} \gtrsim 20$ MeV/c



long range
correlations

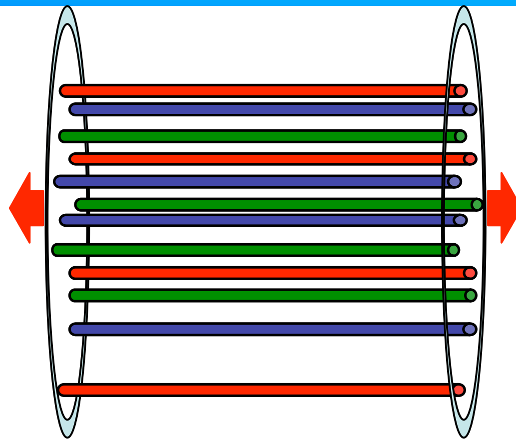
Why Long Range Correlations?

Dumitru, Gelis, McLerran, Venugopalan, arXiv:0804.3858



- **must originate at the earliest stages of the collision**
- **like super-horizon fluctuations in the Universe**
- **information on particle production mechanism**

Flux Tubes and Glasma



Flux Tubes: longitudinal fields early on

- Flux tube transverse size $\sim Q_s^{-2}$

- Number of flux tubes $\dfrac{Area}{area/tube} \propto Q_s^2 R_A^2$

- Tubes→quarks+gluons
Single flux tube phase space density of gluons $\sim \alpha_s^{-1}(Q_s)$

- Gluon rapidity density $\boxed{\dfrac{dN}{dy} \propto \alpha_s^{-1}(Q_s) Q_s^2 R_A^2}$

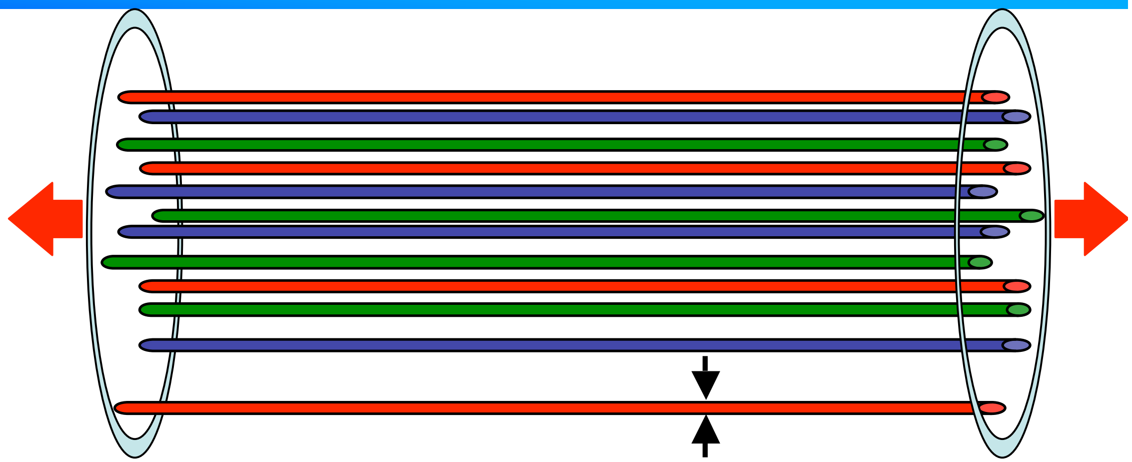
Kharzeev & Nardi

Flux Tubes and Correlations

Correlation function

- Partons from the **same tube** are correlated
- Rapidity reach: Causally disconnected

See: Dusling et. al. arXiv:0911.2720



flux tube transverse size ~ $Q_s^{-1} << R_A$

$$\boxed{c(\mathbf{x}_1, \mathbf{x}_2) \sim \mathcal{R}\, \delta(\vec{r}_{t,1} - \vec{r}_{t,2})}$$

- Correlation Strength $\mathcal{R} \propto \langle \#tubes \rangle^{-1} = (Q_s R_A)^{-2}$
- Long range **Glasma** fluctuations scale the phase space density $\boxed{\mathcal{R} \frac{dN}{dy} \propto \alpha_s^{-1}(Q_s^2)}$

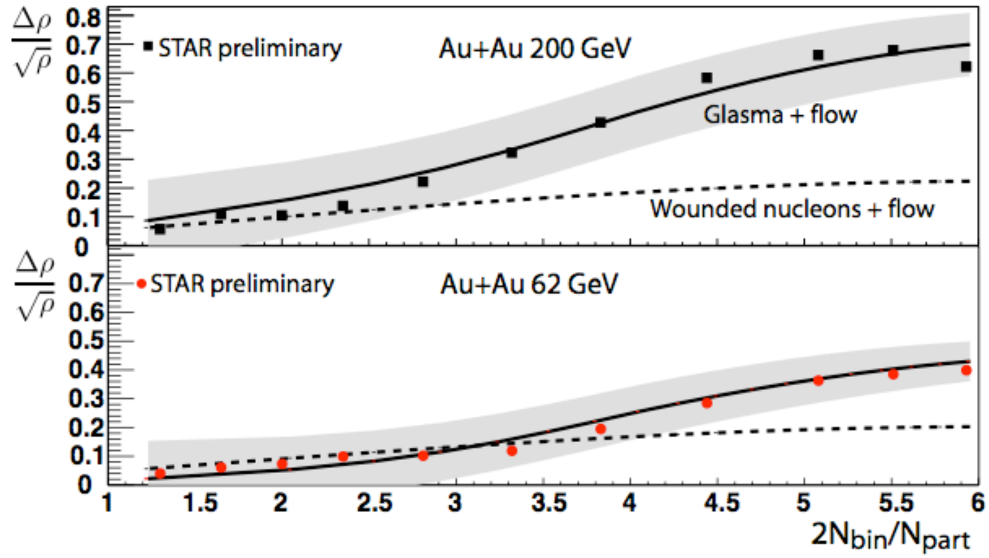
Dumitru, Gelis, McLerran & Venugopalan;
Gavin, McLerran & GM

- Energy and centrality dependence $Q_s^2 \propto (\sqrt{s})^{1/3} (N_{part})^{1/3}$

Energy and System Dependence

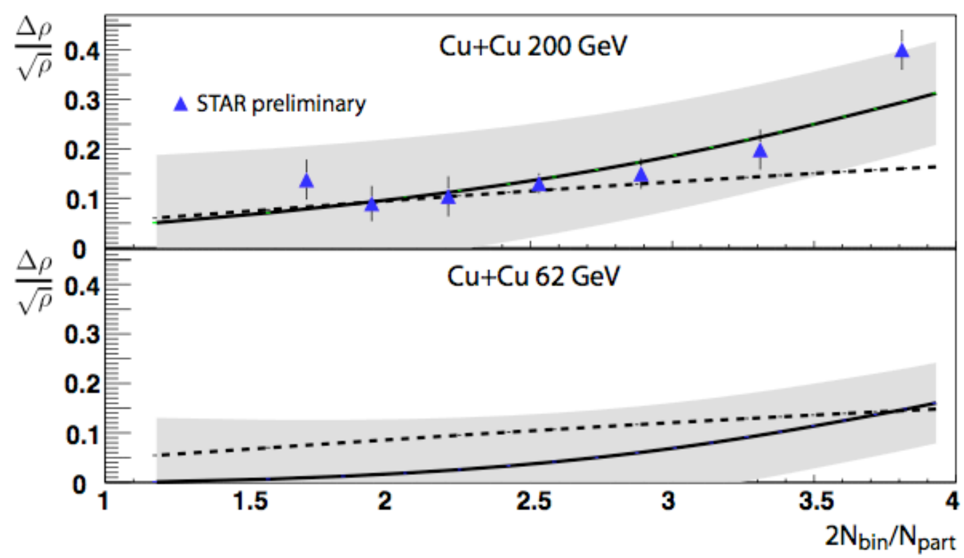
$$\Delta\rho \equiv pairs - (singles)^2$$

$$\propto \iint c(\vec{x}_1, \vec{x}_2) f(\vec{x}_1, \vec{p}_1) f(\vec{x}_2, \vec{p}_2)$$



Blast Wave

- Boltzmann Dist. → $f(p,x)$
- Scale factor to fit 200 GeV only
- Centrality dependence on blast wave parameters (v and T) → 10% uncertainty
- Blast wave only (dashed) **fails**

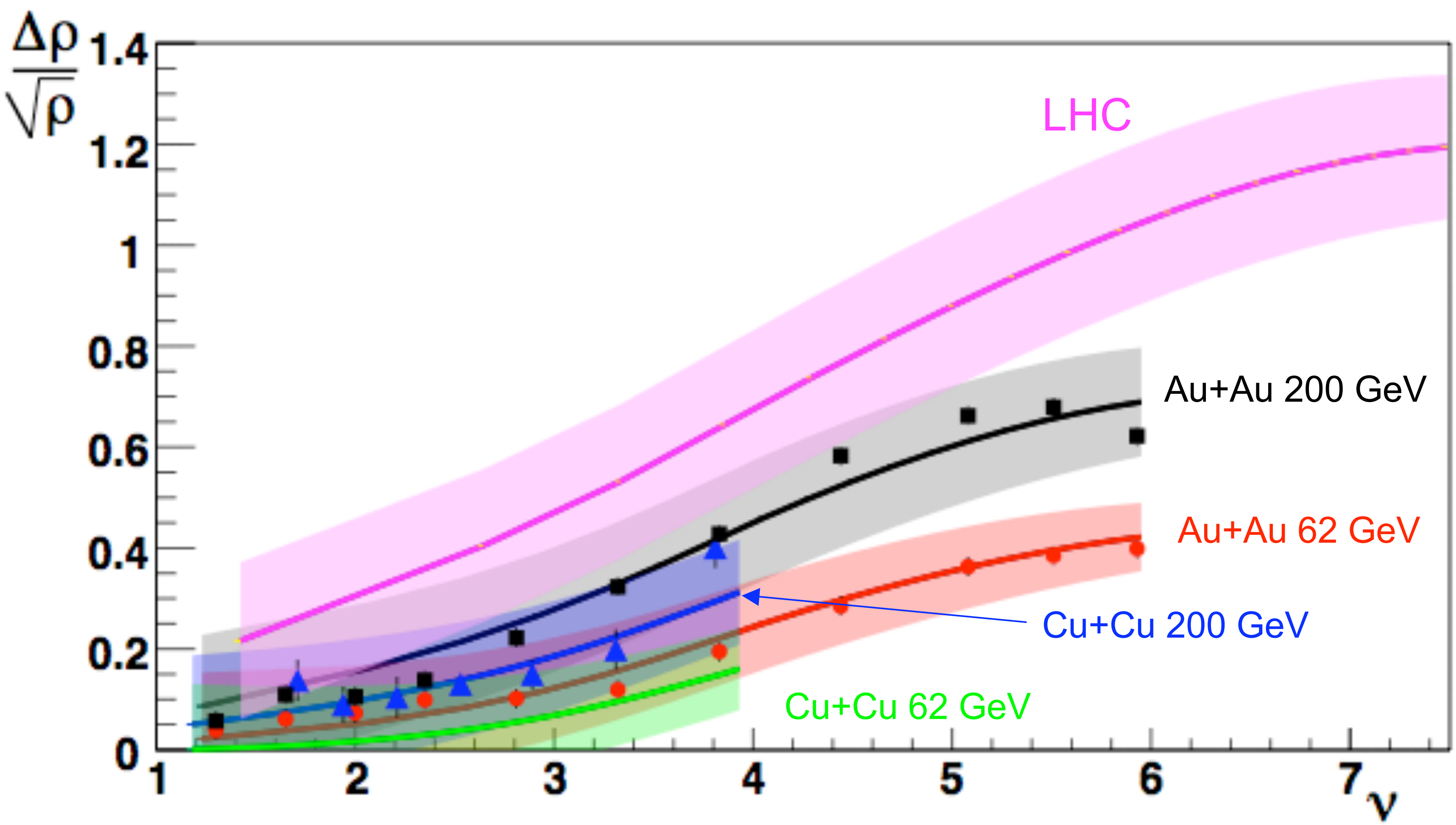


Glasma Dependence

$$\frac{\Delta\rho}{\sqrt{\rho}} = \mathcal{R}\frac{dN}{dy} \times (blast\ wave)$$

- Q_s dependence: 200 GeV Au+Au ⇒ 62 GeV, Cu+Cu

Comparison and LHC



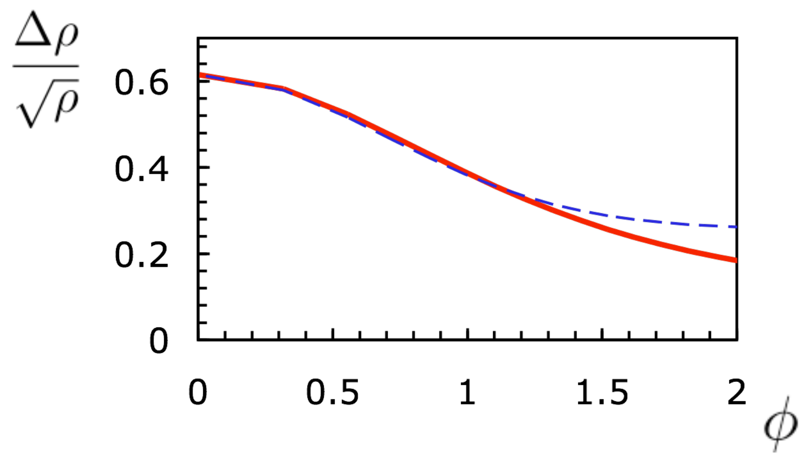
Caution: Blast Wave parameters for LHC taken from Au+Au 200 GeV

Angular Correlations

Fit using Gaussian + offset

- Range: $-\pi/2 < \phi < \pi/2$

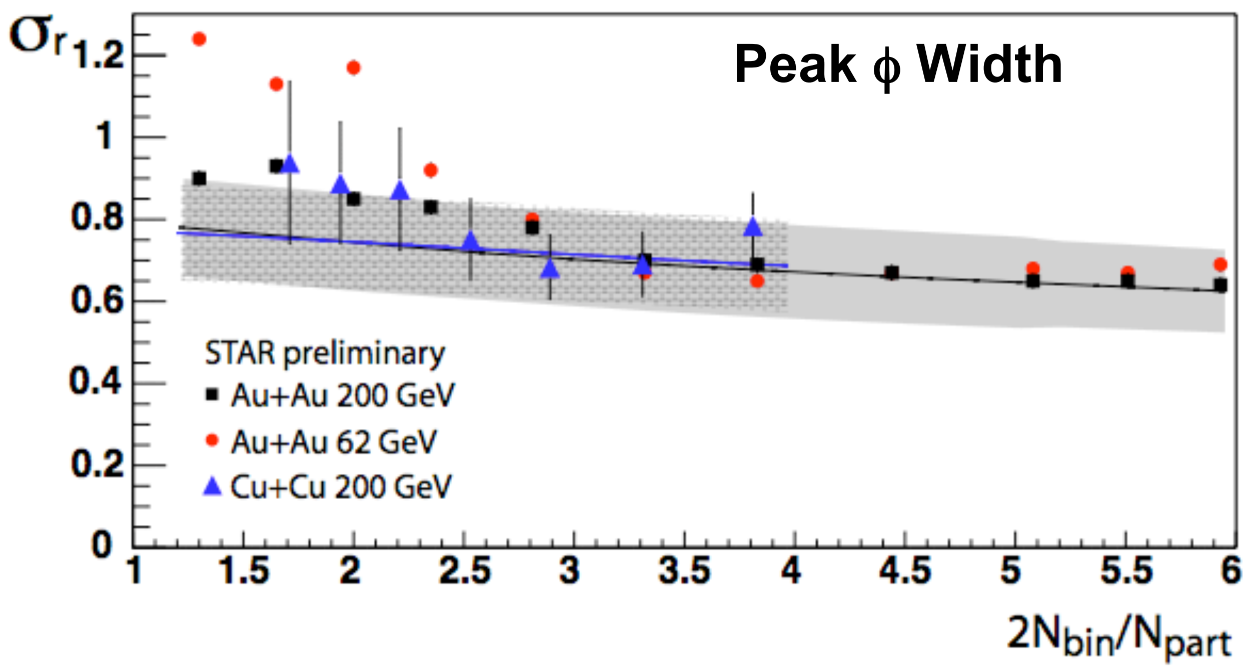
- Error band: 20% shift in fit range



- Uncertainty due to experimental definition of peak

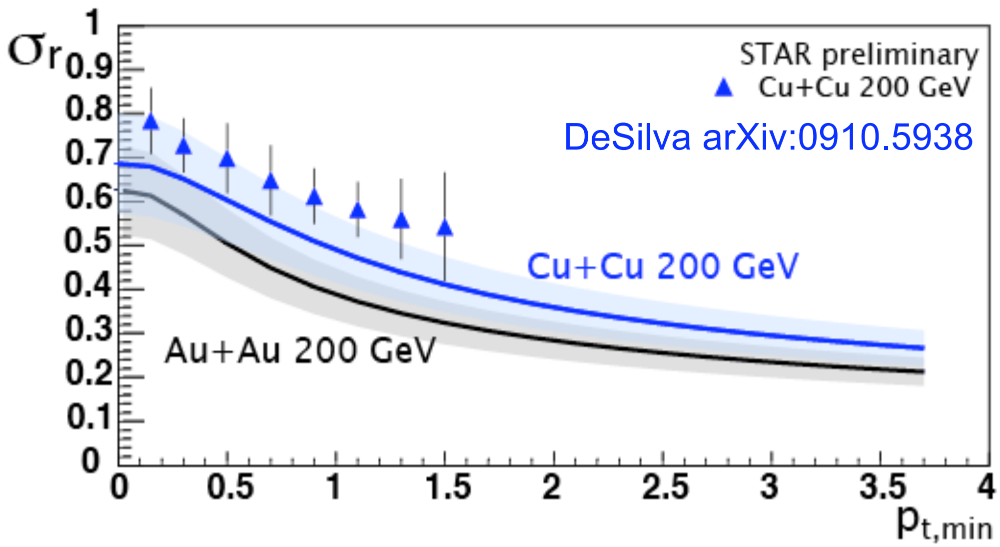
- Computed angular width is approximately independent of energy

- The width should decrease with increasing p_t range

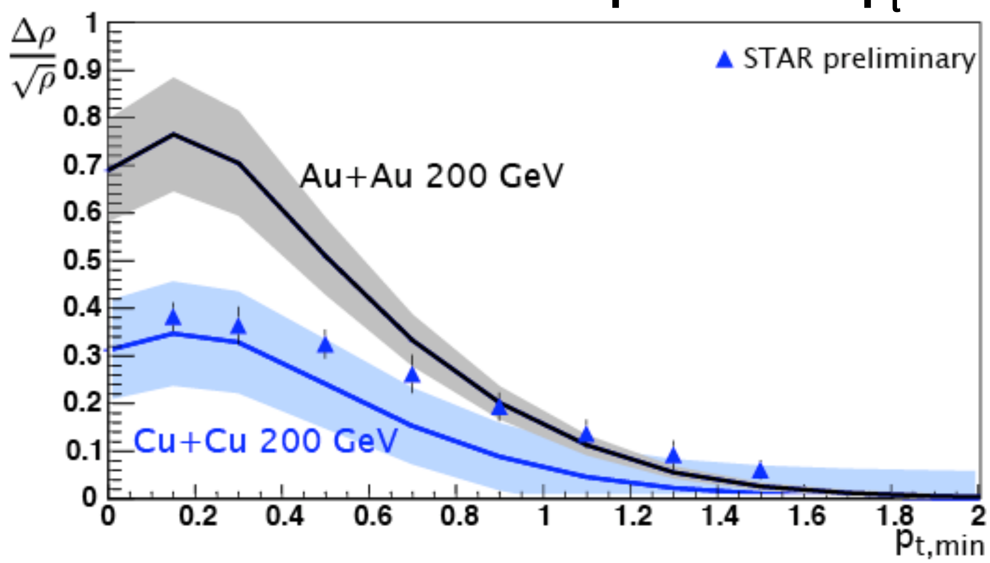


Soft Ridge vs. p_t

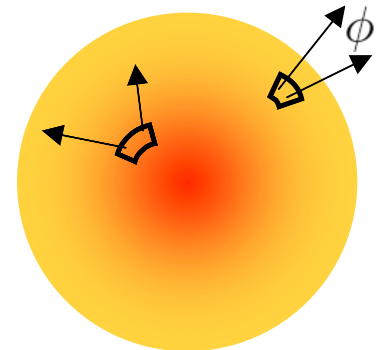
Most Central ϕ Width vs. p_t



Most Central Amplitude vs. p_t



Examine bulk correlations in different p_t ranges

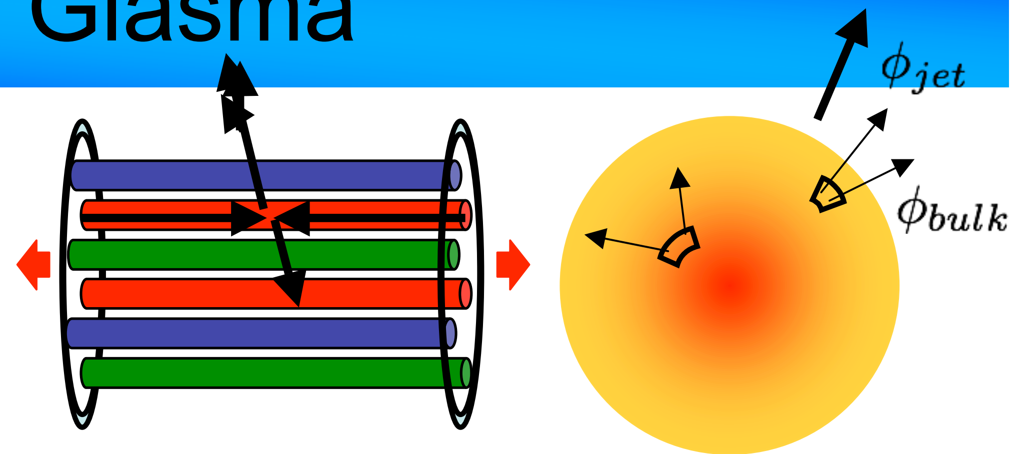


- The amplitude drops and the azimuthal width narrows with increasing $p_{t,min}$
- Bulk correlations alone might not explain the data at higher p_t
- Jet-Bulk and Jet-Jet correlations should have an increasing effect with p_t
- Jet contributions should force the correlation width to approach the jet correlation width

Jets + Glasma

Jet-Bulk correlation function

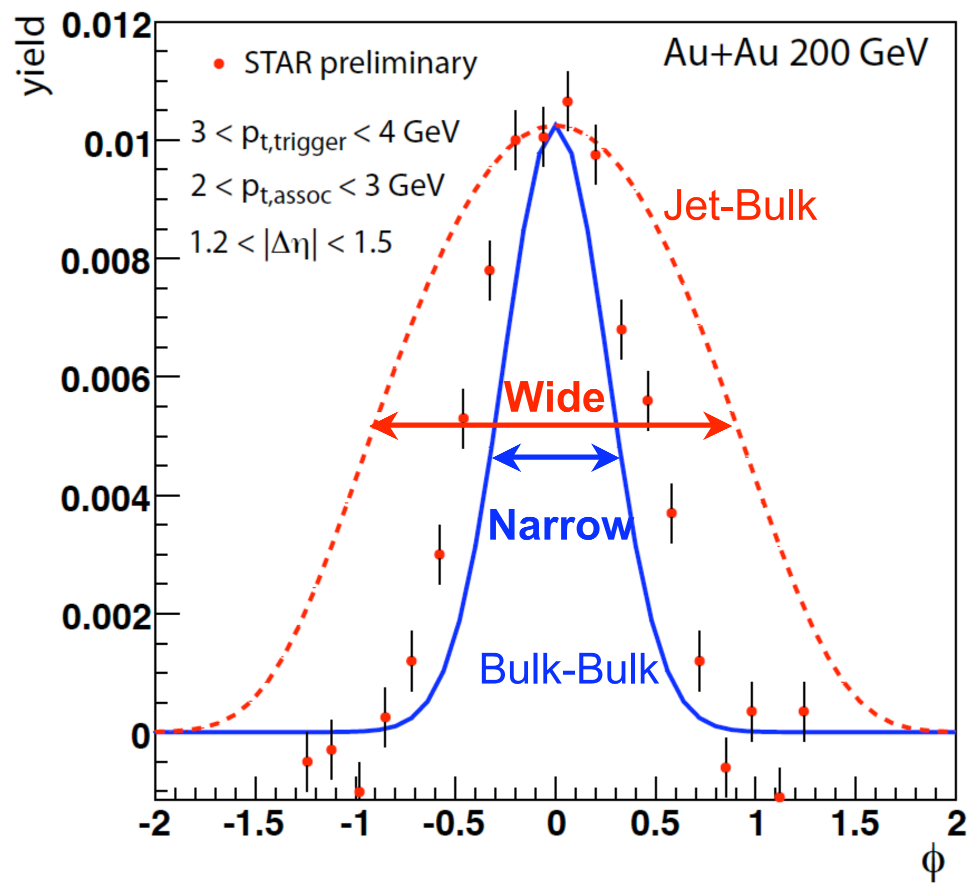
$$c(\mathbf{x}_1, \mathbf{x}_2) \sim \mathcal{R}_{JB}\,\delta(\vec{r}_{t,jet} - \vec{r}_{t,tube})$$



- Correlation strength $\boxed{\mathcal{R}_{JB} = \mathcal{R}}$

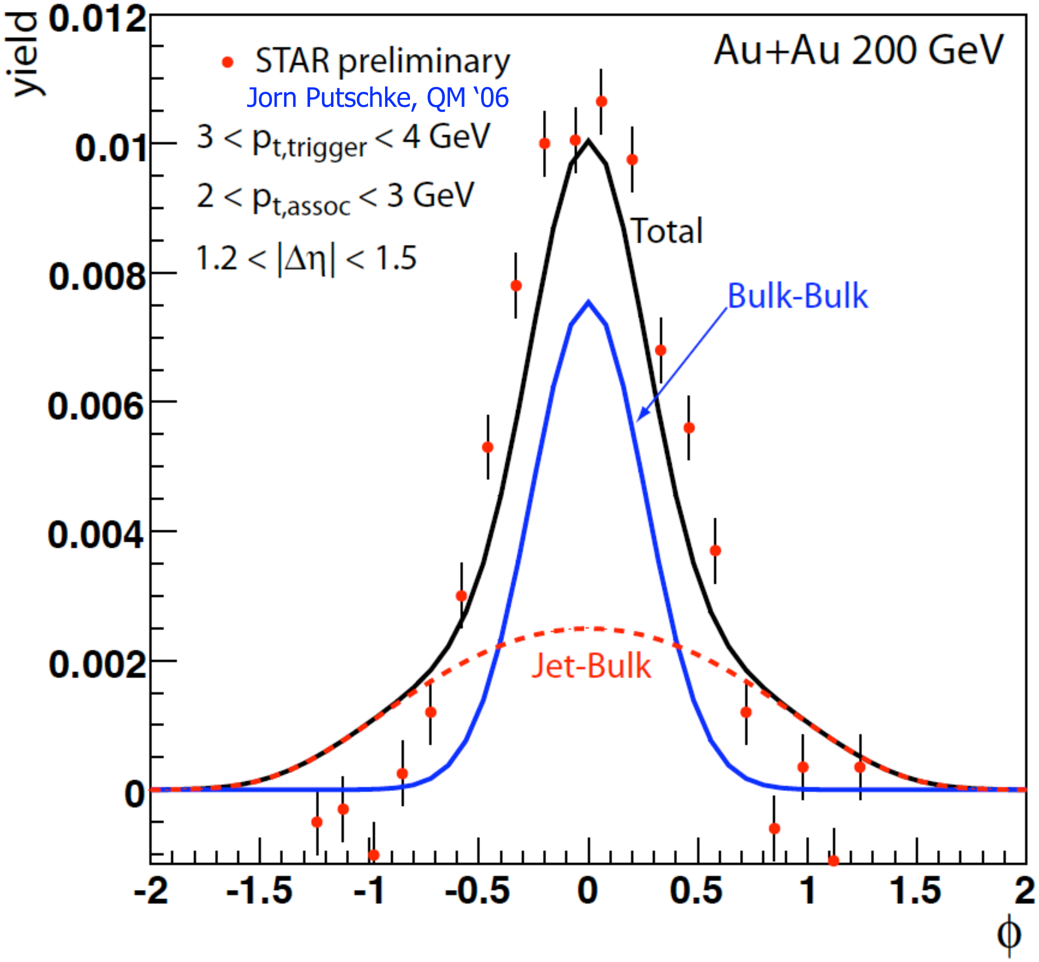
- Yield of associated particles per jet trigger; different p_t ranges $\frac{1}{N_{trig}} \frac{d^2N}{d\Delta\phi\, d\Delta\eta}$

- $f(x_1,p_1) \rightarrow$ jet p_t range
  $f(x_2,p_2) \rightarrow$ bulk associated p_t range



Jet-Bulk width similar to E. Shuryak, Phys. Rev. C 76, 047901 (2007)

Hard Ridge



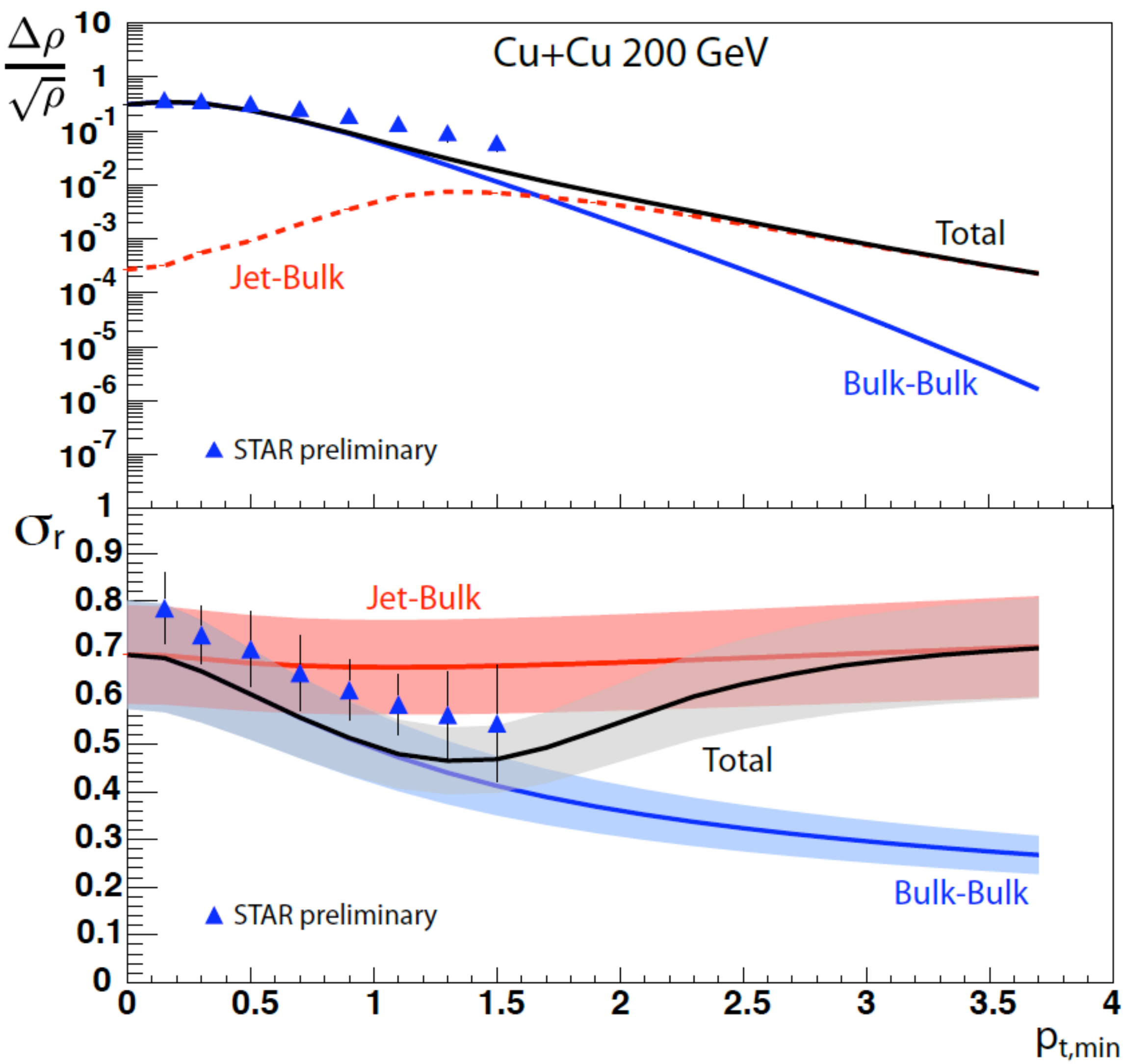
dN/dp_t constrains jet fraction

- Bulk particles: Blast Wave
- Jet particles: Total - BW
- Jet scale $\propto Q_s$; take 1.25 GeV

Jets + Flow Fit the Hard Ridge

- Bulk-Bulk correlations ~70%.
- Bulk-Bulk + Jet-Bulk better azimuthal agreement

The Ridge: From Soft to Hard



Bulk Correlations

- Amplidude decreases with $p_{t,min}$
- Narrow width from flow alone

Jet+Bulk Correlations

- Jet contribution dominates with increasing $p_{t,min}$
- σ_r widening at large $p_{t,min}$ would indicate significant contribution from jet correlations out in the ridge

Summary

Ridge Azimuthal Width

- Flow induces angular correlations
- *Azimuthal width vs. p_t can distinguish flow from jets*

Long Range Correlations

- PHOBOS measurement
- Implications on particle production mechanism

Glasma + Blast Wave

- Blast Wave fixed by single particle spectra
- Glasma fixed by dN/dy and 200 GeV Au+Au
- *Predicts the height and azimuthal width of the Soft and Hard Ridge*
- Predict energy, centrality, system, and p_t dependence

Bulk Correlations Dominate the Hard Ridge

Backup Slides

Hard vs. Soft Ridge

hard ridge explanations -- jet interactions with matter

- N. Armesto, C.A. Salgado, U.A. Wiedemann, Phys. Rev. Lett. 93, 242301 (2004)
- P. Romatschke, Phys. Rev. C 75, 014901 (2007)
- A. Majumder, B. Muller, S. A. Bass, Phys. Rev. Lett. 99, 042301 (2007)
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- C. Y. Wong, arXiv:0712.3282 [hep-ph]
- R. C. Hwa, C. B. Yang, arXiv:0801.2183 [nucl-th]
- T. A. Trainor, arXiv:0708.0792 [hep-ph]
- A. Dumitru, Y. Nara, B. Schenke, M. Strickland, arXiv:0710.1223 [hep-ph]
- E. V. Shuryak, Phys. Rev. C 76, 047901 (2007)
- C. Pruneau, S. Gavin, S. Voloshin, Nucl.Phys.A802:107-121,2008

soft ridge -- similar but no jet -- collective behavior

- S. Gavin and M. Abdel-Aziz, Phys. Rev. Lett. 97, 162302 (2006)
- S. A. Voloshin, Phys. Lett. B 632, 490 (2006)
- S. Gavin and G. Moschelli, arXiv:0806.4366 [nucl-th]
- A. Dumitru, F. Gelis, L. McLerran and R. Venugopalan, arXiv:0804.3858 [hep-ph]
- S. Gavin, L. McLerran, G. Moschelli, arXiv:0806.4718; arXiv:0910.3590 [nucl-th]
- F. Gelis, T. Lappi, R. Venugopalan, arXiv:0807.1306 [hep-ph]
- J. Takahashi et. al. arXiv:0902.4870 [nucl-th]

Blast Wave Single Particle Fits

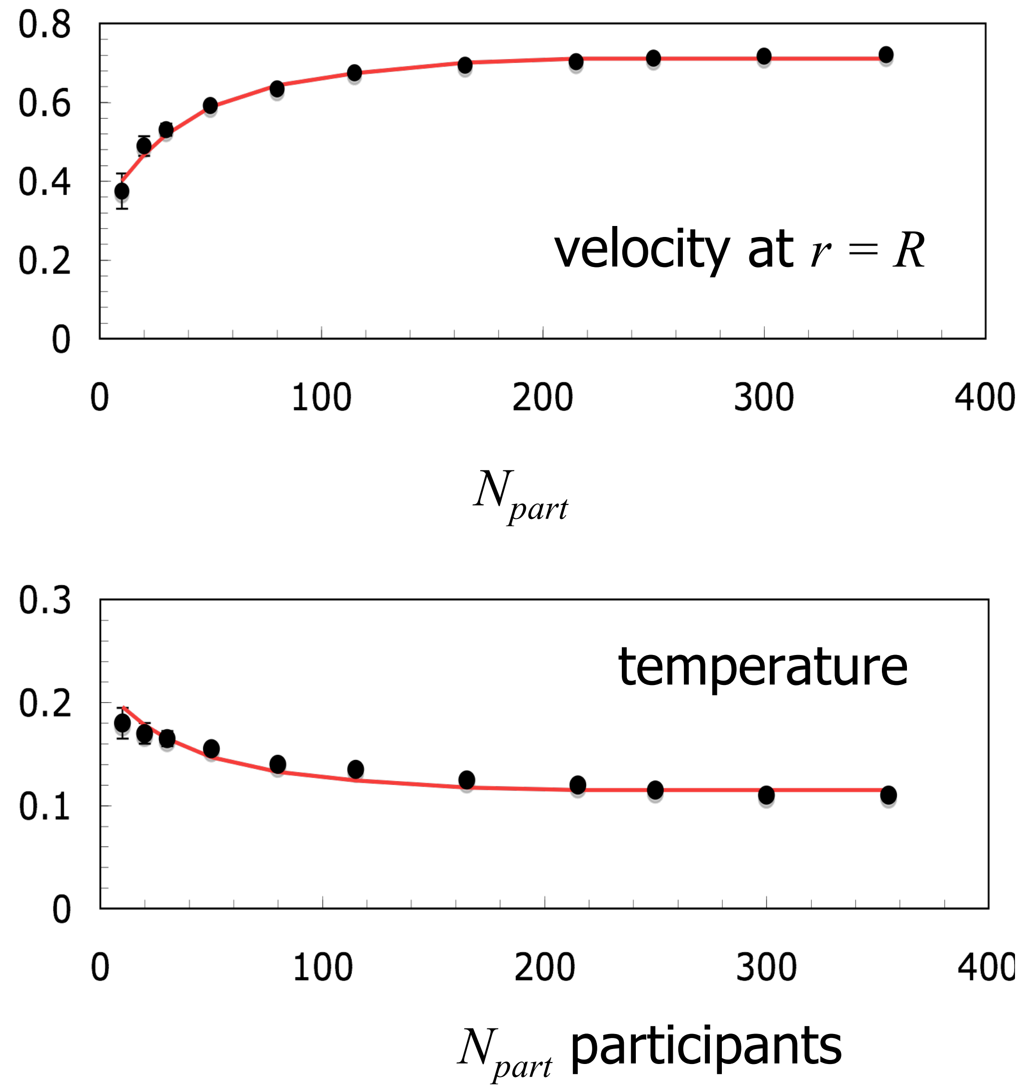
Akio Kiyomichi, PHENIX

fit momentum spectra in 200 GeV Au+Au

10% systematic uncertainty in scale of v and T

62 GeV Au+Au:

5% smaller v, 10% smaller T



Blast Wave and the Correlation Function

Schnedermann, Sollfrank & Heinz

- Single Particle Spectrum
- Correlation Function

$$\rho_1(\vec{p}) \equiv \frac{dN}{dyd^2p_t} = \int_{freezout} f(\vec{x},\vec{p})$$

$$\gamma_t \vec{v}_t = \lambda \vec{r}$$

A Hubble like expansion in used in a Boltzmann Distribution

$$\Delta\rho(\vec{p}_1,\vec{p}_2) \equiv pairs - (singles)^2$$

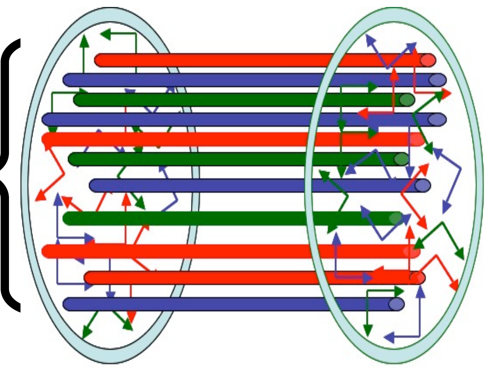
$$\Delta\rho(\vec{p}_1,\vec{p}_2) = \iint_{freezout} c(\vec{x}_1,\vec{x}_2) f(\vec{x}_1,\vec{p}_1) f(\vec{x}_2,\vec{p}_2)$$

$$\Delta\rho(\eta,\phi) = \iint_{momenta} \Delta\rho(\vec{p}_1,\vec{p}_2)$$

$$\rho_{ref} = \iint_{momenta} \rho_1(\vec{p}_1)\rho_1(\vec{p}_2)$$

$$\iint_{momenta} \Delta\rho = \iint_{positions} c = \langle N\rangle^2 \mathcal{R}$$

Correlation Strength



strength ***R***

$$\langle N\rangle^2 \boldsymbol{R} \equiv \iint_{volume} c(x_1,x_2) =$$

$$= \iint_{volume} \{n_2(x_1,x_2) - n_1(x_1)n_1(x_2)\} = \langle N(N-1)\rangle - \langle N\rangle^2$$

K flux tubes, assume

$$\langle N\rangle_K = \mu K, \qquad \langle N^2\rangle_K - \langle N\rangle_K^2 = \sigma^2 K$$

K varies event-by-event

$$\langle N\rangle = \mu\langle K\rangle, \qquad \langle N^2\rangle - \langle N\rangle^2 = \sigma^2\langle K\rangle + \mu^2\left(\langle K^2\rangle - \langle K\rangle^2\right)$$

$$\boldsymbol{R} = \frac{\sigma^2 - \mu}{\mu^2}\frac{1}{\langle K\rangle} + \frac{\langle K^2\rangle - \langle K\rangle^2}{\langle K\rangle^2}$$

fluctuations per tube number of tubes

Jet Correlation Strength

$$\mathcal{R} = \frac{\langle N(N-1)\rangle - \langle N\rangle^2}{\langle N\rangle^2}$$

Pruneau, Gavin, Voloshin
Phys.Rev. C66 (2002) 044904

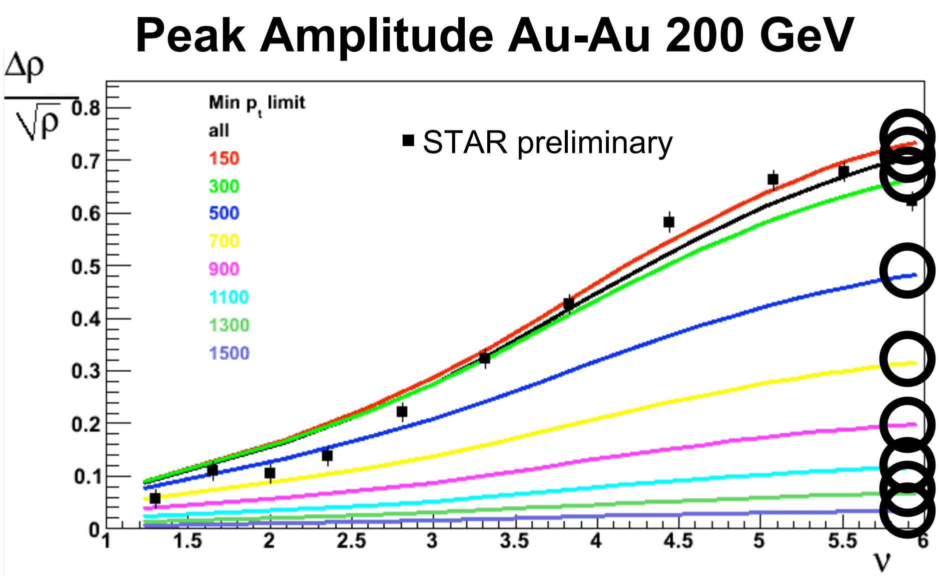
$$\mathcal{R}_{JB} = \frac{\langle N_J N_B\rangle - \langle N_J\rangle\langle N_B\rangle}{\langle N_J\rangle\langle N_B\rangle}$$

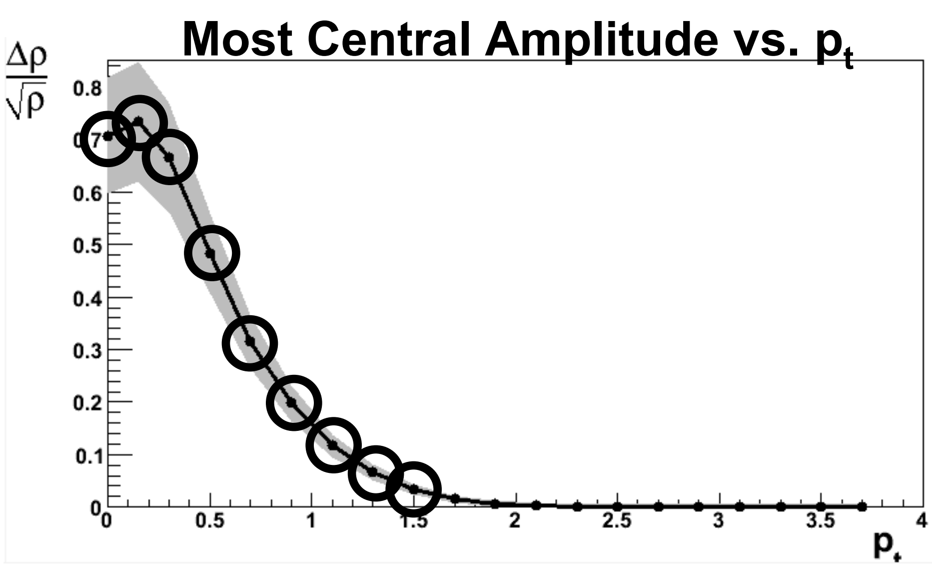
$$= \frac{\alpha\beta\langle N(N-1)\rangle - \alpha\beta\langle N\rangle\langle N\rangle}{\alpha\beta\langle N\rangle\langle N\rangle}$$

$$\boxed{\begin{aligned}\langle N_B\rangle &= \beta\langle N\rangle \\ \langle N_J\rangle &= \alpha\langle N\rangle \\ \langle N_J N_B\rangle &= \alpha\beta\langle N(N-1)\rangle\end{aligned}}$$

$$\Longrightarrow \quad \boxed{\mathcal{R}_{JB} = \mathcal{R}}$$

Soft Ridge vs. p_t





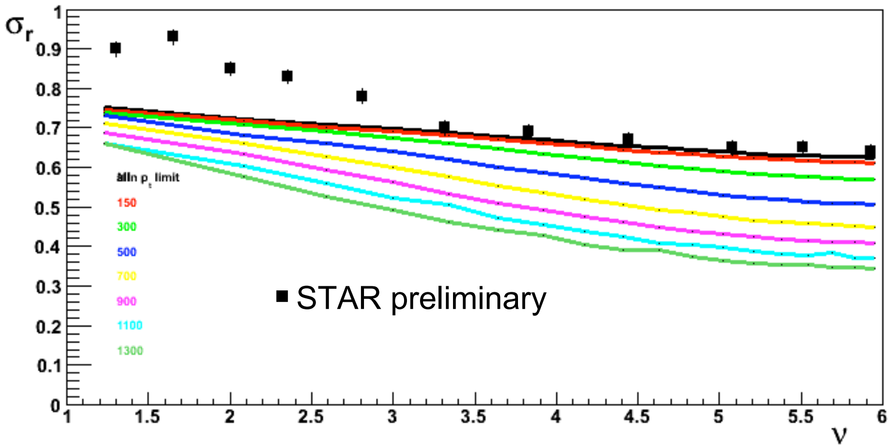
$$\left(\frac{\Delta\rho}{\sqrt{\rho_{ref}}}\right)_{p_t > p_{t,min}}$$

$$= \frac{\iint_{p_{t,min}} \Delta\rho(\vec{p}_{t1}, \vec{p}_{t2})}{\{\iint_{p_{t,min}} \rho_{1(\vec{p}_{t1})}\rho_{1(\vec{p}_{t2})}\}^{1/2}}$$

- Increase the lower p_t limit of the soft ridge calculation toward the hard ridge range.
- As the lower p_t limit is increased less particles are available for correlations.
- Correlation amplitude for the most central collision plotted vs. the lower p_t limit.

Soft Ridge vs. p_t

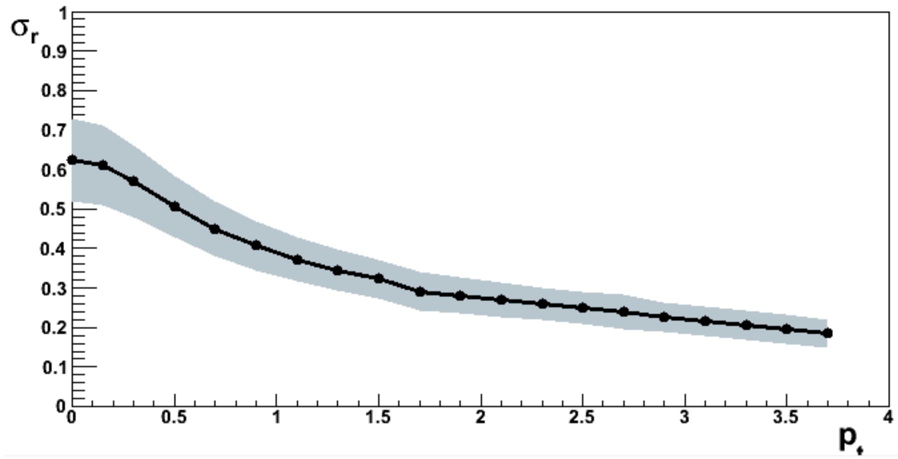
Peak φ Width Au-Au 200 GeV



Angular width from

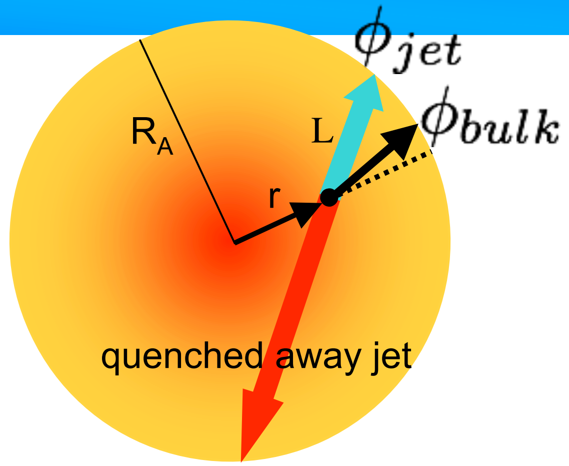
$$\left(\frac{\Delta\rho}{\sqrt{\rho_{ref}}}\right)_{p_t > p_{t,min}}$$

Most Central φ Width vs. p_t



- Higher p_t particles received a larger radial push ⇒ narrower relative angle.

Quenching + Flow



E. Shuryak, Phys. Rev. C 76, 047901 (2007)

- Surviving jets tend to be more radial, due to quenching.

- Jet path

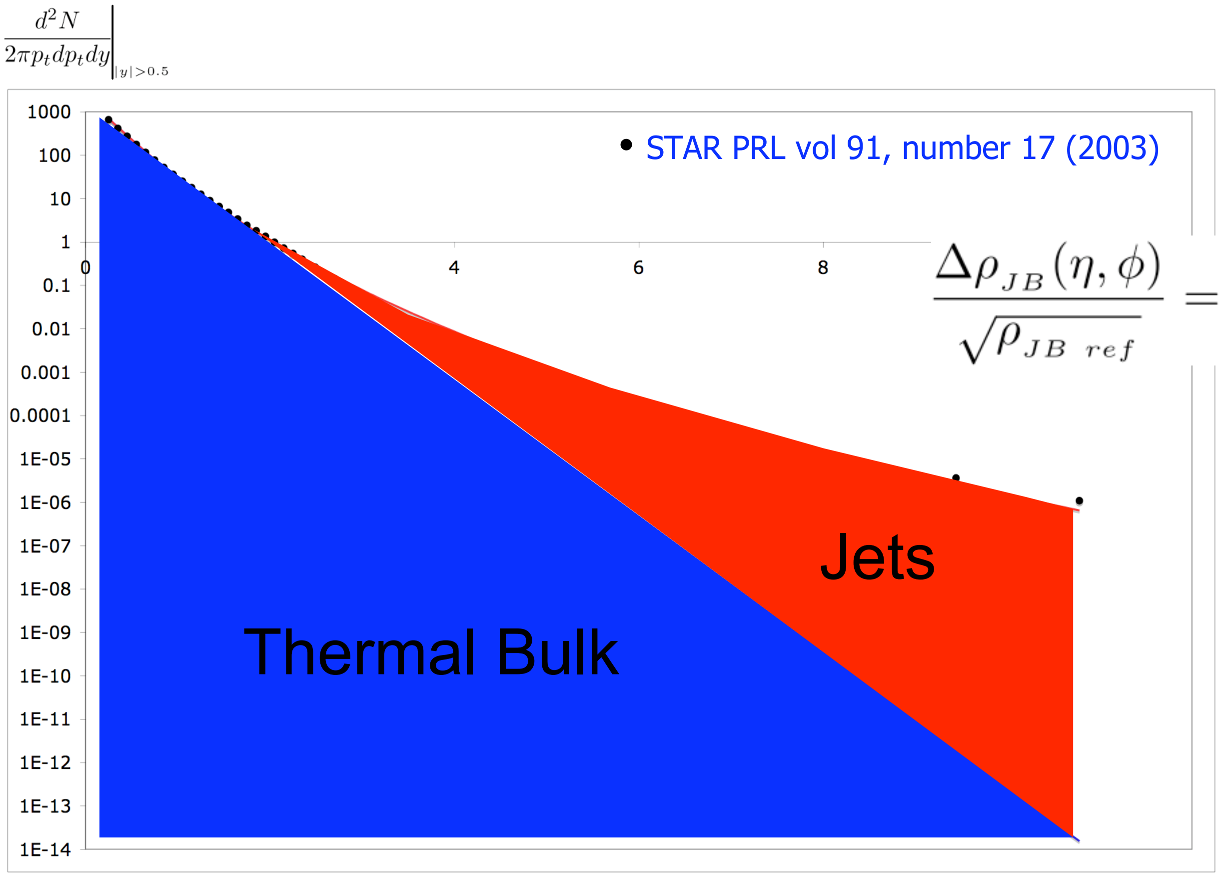
$$L(r, \phi_{jet}) = \sqrt{R_A^2 - r^2 \sin^2(\phi_{jet})} - r\cos(\phi_{jet})$$

- Survival probability $$S(\vec{x_1}, \vec{x_2}) = e^{\frac{-L(r,\phi_{jet})}{\rho\sigma}}$$

- Production probability $$P_{prod}(r) \propto \left(1 - \frac{r^2}{R^2}\right)$$

- Jet Distribution $$f(\vec{x}, \vec{p}) = \frac{A}{p^n} P_{prod}(r) S(r, \phi_{jet})$$

Two Contributions

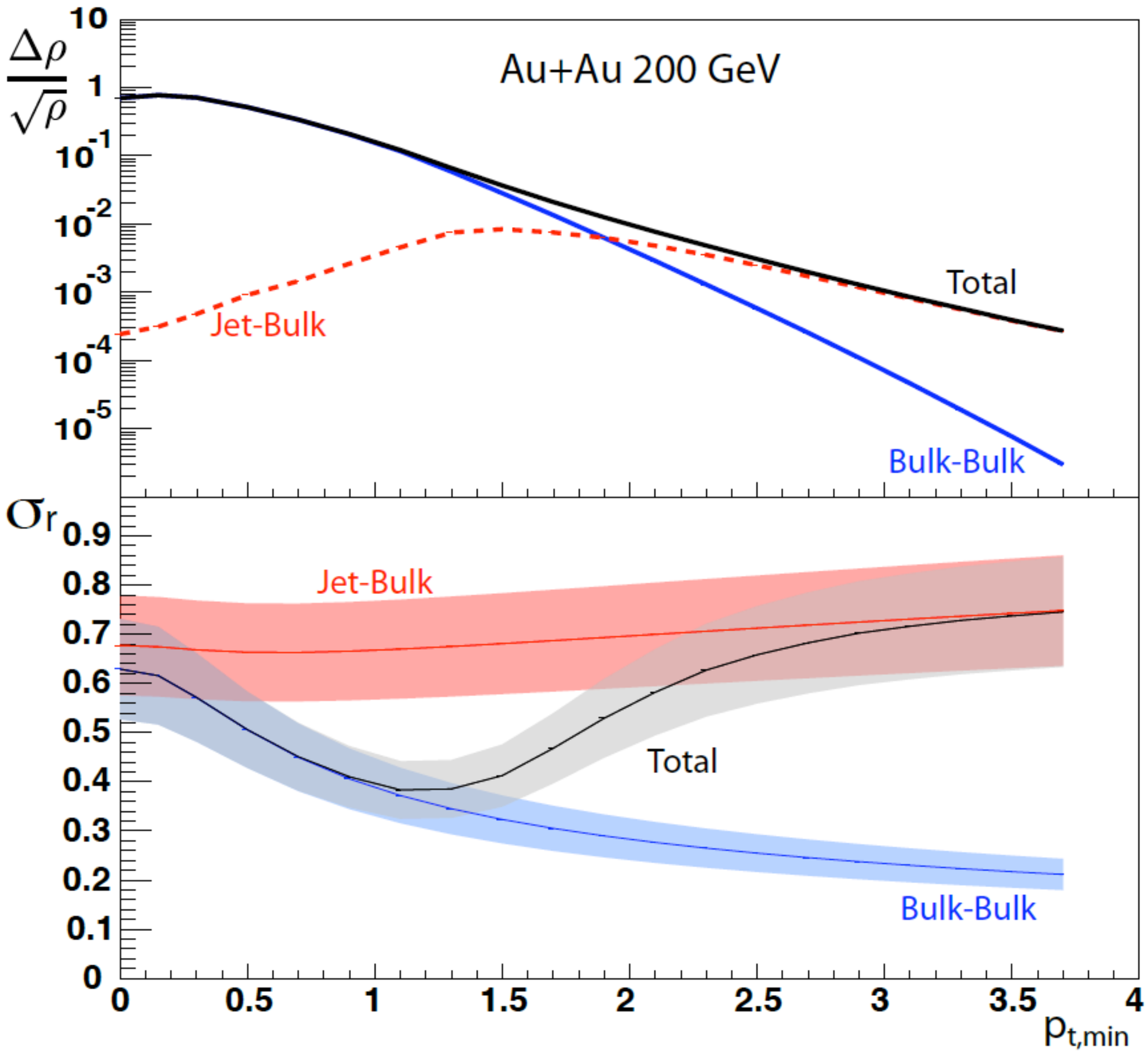


“Jet-Bulk” correlations

- Both the Bulk-Bulk and Jet-Bulk contributions are weighted by the fraction of bulk or jet particles to the total.

$$\frac{\Delta\rho(\eta,\phi)}{\sqrt{\rho_{ref}}} = \frac{\Delta\rho_{BB}(\eta,\phi)}{\sqrt{\rho_{BB\ ref}}}\left(\frac{Bulk}{fraction}\right) + \frac{\Delta\rho_{JB}(\eta,\phi)}{\sqrt{\rho_{JB\ ref}}}\left(\frac{Jet}{fraction}\right)$$

The Ridge: From Soft to Hard



Bulk Correlations

- Amplidude decreases with $p_{t,min}$
- Narrow width from flow alone

Jet+Bulk Correlations

- Jet contribution dominates with increasing $p_{t,min}$
- σ_r widening at large $p_{t,min}$ would indicate significant contribution from jet correlations out in the ridge